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THICKNESS EFFECTS ON MATERIAL PROPERTIES IN A GLASS/THERMOPLASTIC P.E.T. INJECTION MOLDING COMPOUND

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THICKNESS EFFECTS ON MATERIAL PROPERTIES IN A GLASS/THERMOPLASTIC P.E.T. INJECTION MOLDING COMPOUND

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ABSTRACT

Rynite®* 545, a commercial short glass fiber/ thermoplastic polyethylene terepthalate system, was injection molded into end-gated rectangular plaques of various thicknesses. The plaques were sectioned and characterized by scanning electron microscopy and by mechanical and thermal expansion tests. The glass fibers are shown to be highly aligned in "boundary layers" near the mold surfaces, and are distributed more randomly away from the mold surfaces. As part thickness increased, the aligned fiber boundary layers occupied a smaller proportion of the cross section, resulting in a decrease in mechanical properties. Tensile moduli are derived for boundary and center layers, which can be used to accurately predict the effective moduli at different thicknesses. In addition, the boundary layer thicknesses at the top and bottom surfaces were unequal, producing noticeable warping for thicker plaques.

*Registered trademark of E. I. du Pont de Nemours & Co., Inc.

INTRODUCTION

As automotive manufacturers seek solutions to weight reduction of structural parts, reinforced plastics will see increasing application. Injection molding offers an attractive low-cost, low cycle-time manufacturing process. An understanding of how mold processing conditions affect the part mechanical properties is fundamental to proper part design. The effect of mold conditions on mechanical behavior in a standard test mold has been studied [1]. The statistical orientation of the fibers together with fiber and matrix properties can be used with variational principles to predict bounds on elastic mechanical properties [2].

In thin sections of an injection molded part, flow conditions can produce highly aligned fibers. This fiber alignment yields highly anisotropic mechanical properties. As thicker parts are injection molded, thickness effects which result in lower mechanical properties must be anticipated. This paper demonstrates the effect of part thickness on mechanical properties in a thermoplastic polyester/glass injection molding compound.

SAMPLE FABRICATION

The plaques were injection molded using Rynite® 545, a 45 weight percent glass/thermoplastic polyethylene terepthalate (PET) compound. The compound was in pellet form and 100 percent virgin polymer was used. Plaques were molded on a 20 oz. NATCO screw-injection-molding machine. Injection conditions were: melt temperature of 575°F (300°C) at an injection pressure of 8 to 12×10^3 psi (55 to 85 MPa), with mold fill time of 1.2 to 2 sec. The mold temperature was 200 to 225°F (95 to 105°C). Overall cycle times are shown in Table 1.

TABLE 1.

Plaque Thickness inch (mm)	Cycle Time seconds
0.125 (3.2)	46
0.241 (6.1)	58
0.466 (11.8)	98

EXPERIMENTAL RESULTS

In demonstrating the effect of part thickness on fiber orientation and mechanical properties, several properties are viewed as important indicators. Among these are the tensile (Young's) modulus, flexural modulus, and thermal expansion coefficients. Scanning electron microscopy was used as a tool to examine the microstructure and subdivide the cross section into layers of uniform orientation. The emphasis is placed on measuring properties in the mold-fill direction, defined as the X-axis. See Figure 1. All samples were taken away from edges or corners of the specimen to avoid local edge effects on fiber orientation.

Electron Microscopy. Scanning electron photomicrographs were taken on a Philips Model PSEM 501. Specimens were polished with alumina paste to 1 μ, then coated by gold sputtering. All photomicrographs were taken of sections in the Y-Z plane (see Figure 1) located at the center of the plaque looking in the X direction. The "bottom" surface is arbitrarily defined as the surface with the knock-out pins.

The presence of the mold surface caused alignment of the fibers primarily in the X direction near the surfaces. The center section away from the surfaces

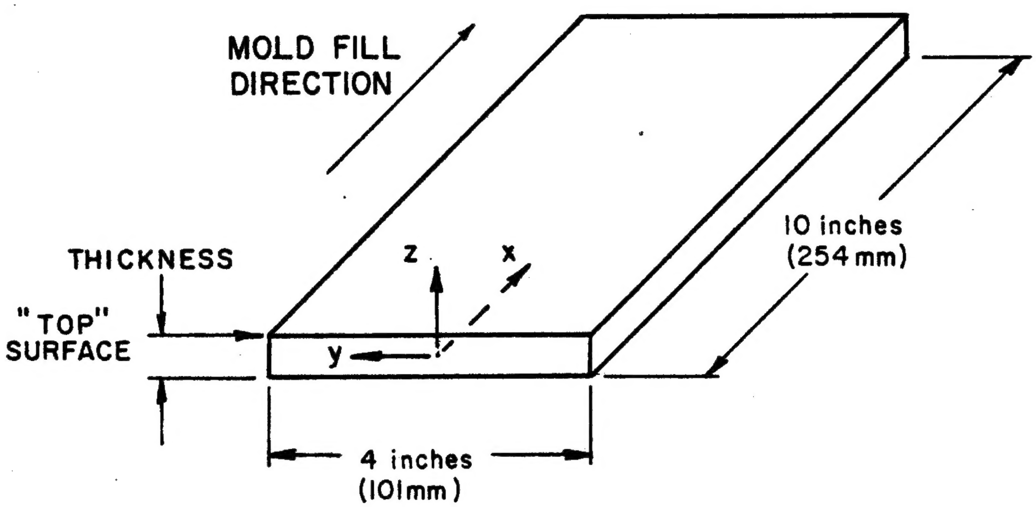

MOLD FILL
DIRECTION
THICKNESS
"TOP"
SURFACE
z
x
y
10 inches
(254 mm)
4 inches
(101mm)

FIGURE 1.

contained fibers aligned primarily in the X-Y plane. Figures 2, 3 and 4 show photomicrographs for plaque thicknesses of 0.125, 0.241 and 0.466 inches (3.2, 6.1 and 11.8 mm) respectively. Approximate dimensions for thicknesses of aligned fiber boundary layers and center layers may be measured directly from the photomicrographs.

A summary of layer thicknesses for aligned boundary layers and center layers is shown in Table 2. Also shown is the plaque curvature $\kappa_x = \Delta\phi/\Delta x$ which is a measure of the warpage of the finished part. The definition of angular curvature is shown in Figure 5; ρ is the radius of curvature.

TABLE 2.

Plaque Thickness	Layer Thickness			Curvature
	Bottom	Center	Top	κ_x
inch		inch		10^{-3} radian/inch
0.125	0.050	0.017	0.058	≃ 0
0.241	0.078	0.104	0.059	1.1
0.466	0.077	0.335	0.054	3.6
mm		mm		10^{-5} radian/mm
3.2	1.3	0.4	1.5	≃0
6.1	2.0	2.6	1.5	4.3
11.8	1.9	8.5	1.4	14.2

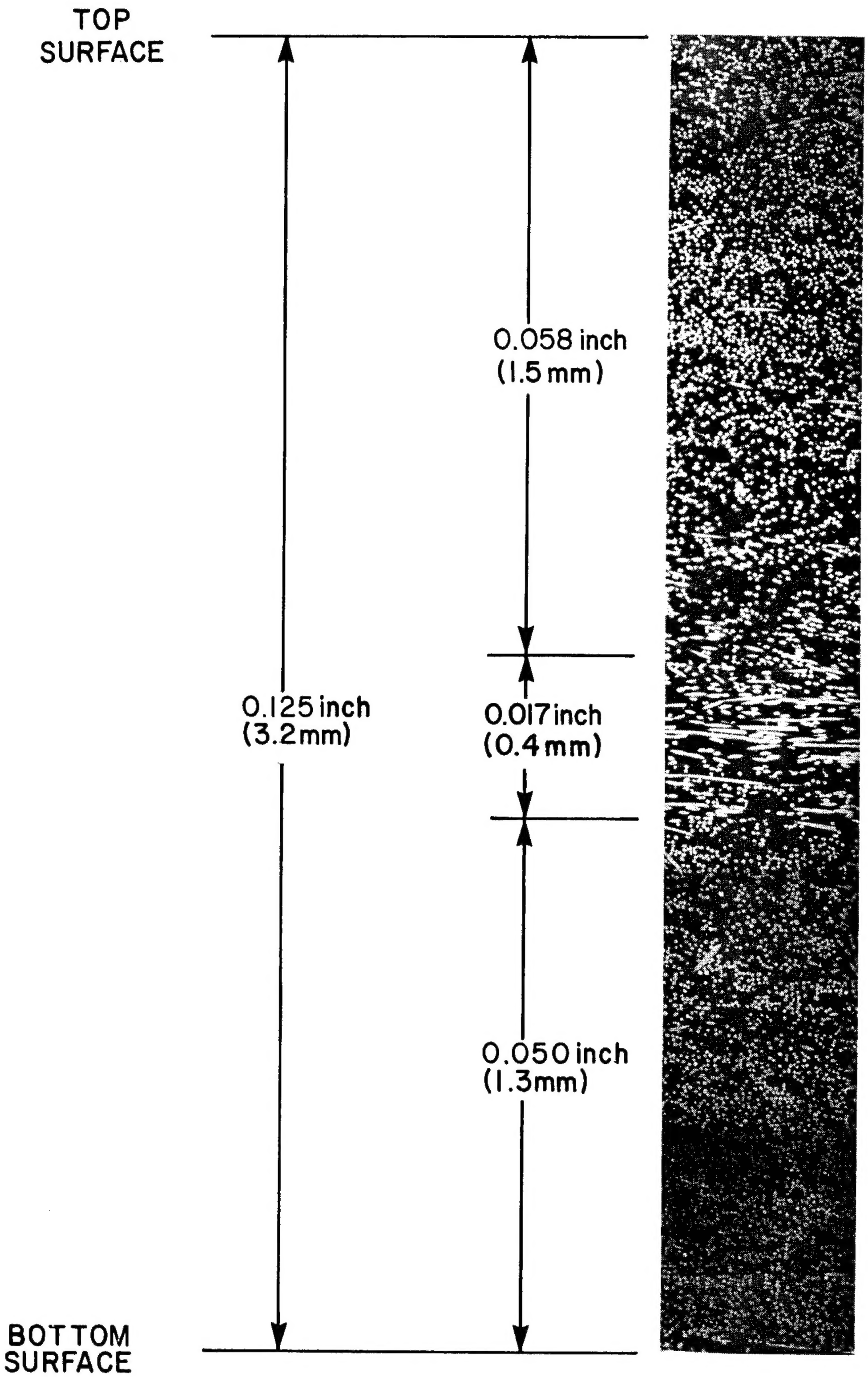

TOP
SURFACE
0.125 inch
(3.2mm)
0.058 inch
(1.5 mm)
0.017 inch
(0.4 mm)
0.050 inch
(1.3mm)
BOTTOM
SURFACE

FIGURE 2.

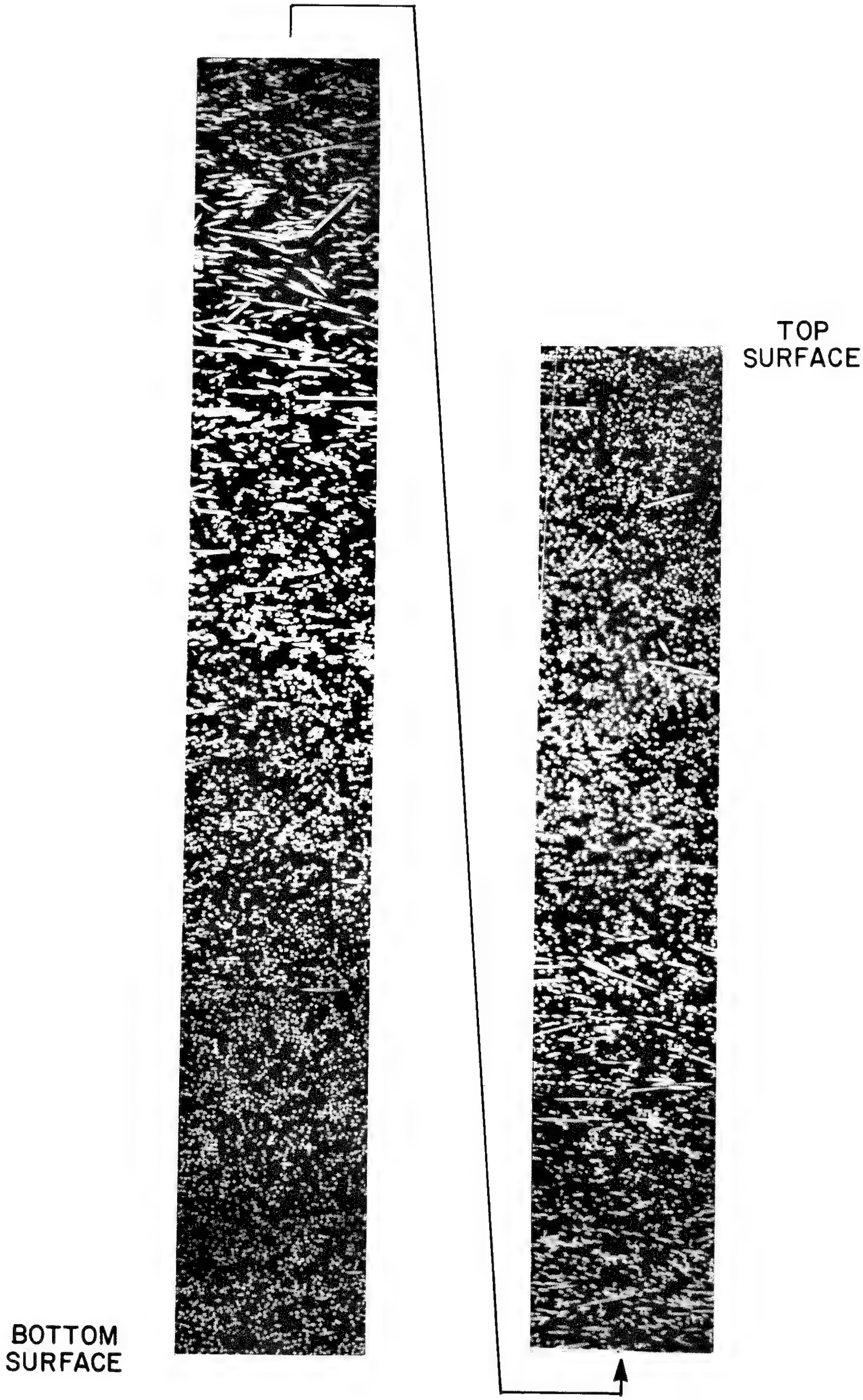


FIGURE 3.

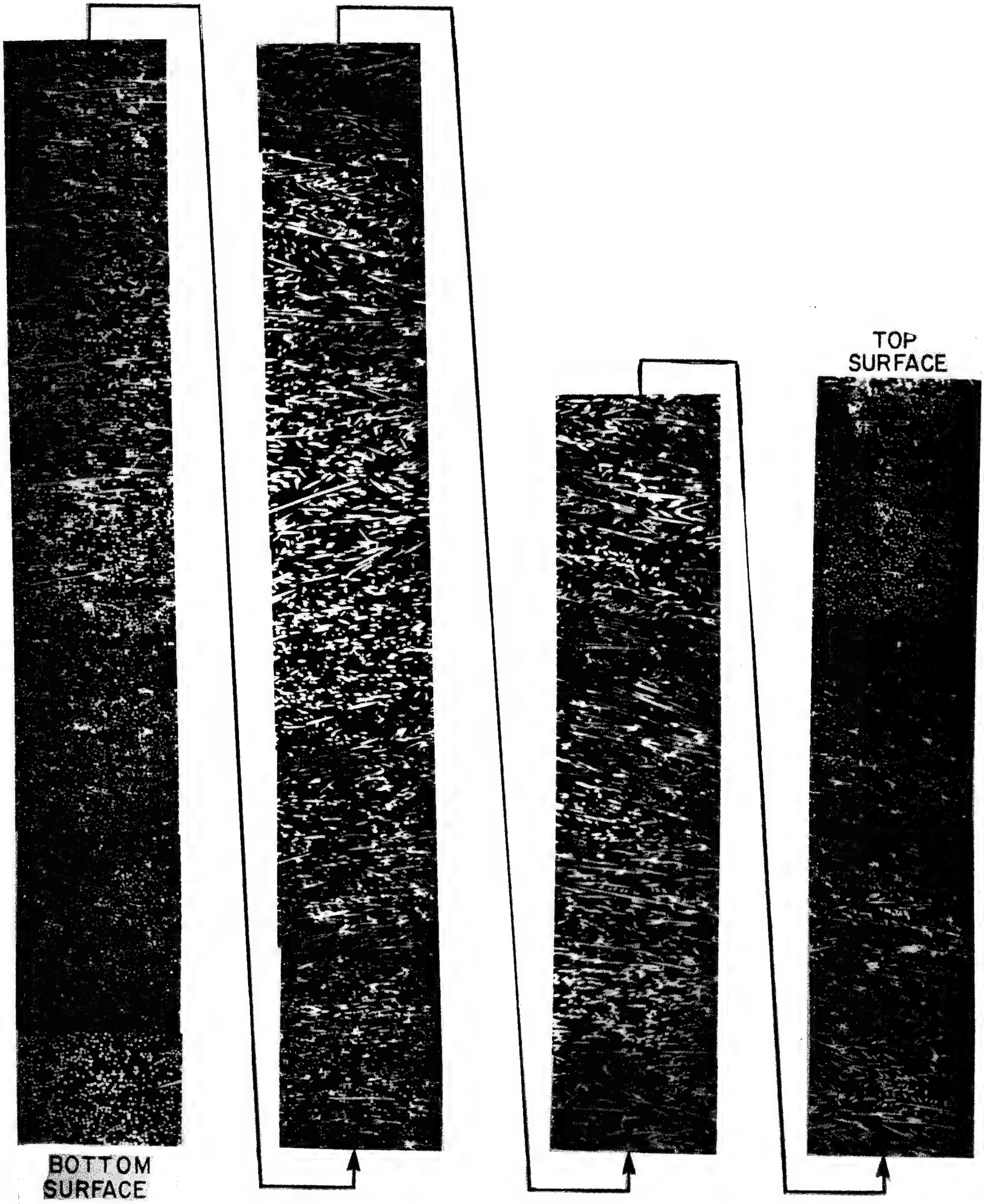
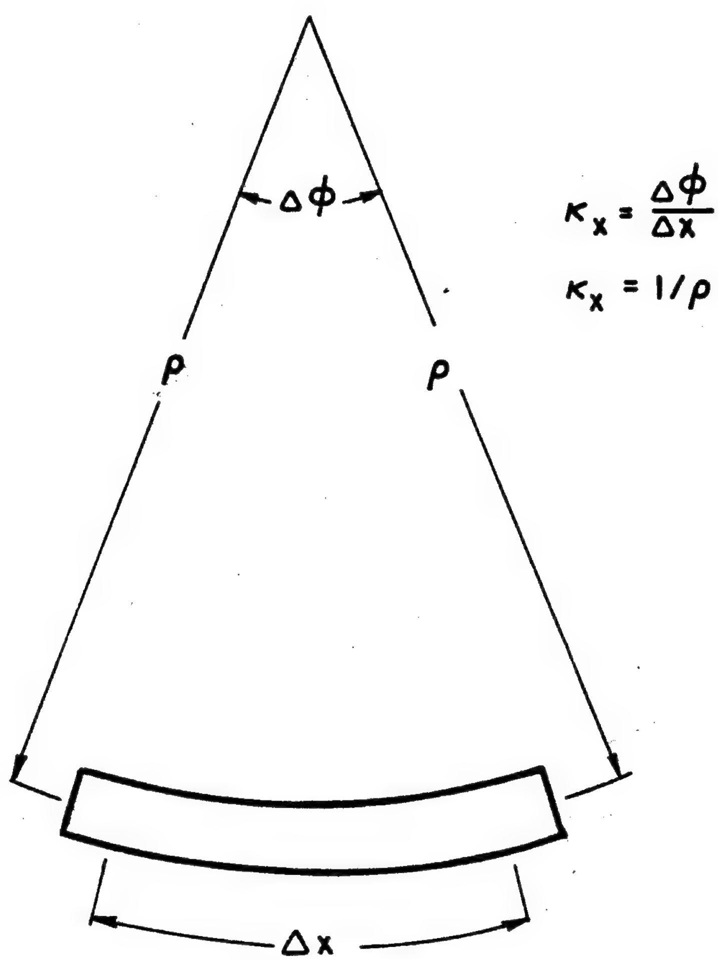


FIGURE 4.



$\Delta\phi$
$\kappa_x = \frac{\Delta\phi}{\Delta x}$
$\kappa_x = 1/\rho$
ρ
ρ
Δx

FIGURE 5.

Mechanical Properties. The influence of the asymmetry of the layers and the changing proportion of aligned fibers can be shown by measurement of the mechanical and thermal expansion properties. Table 3 shows the tensile and flexural modulus results for samples tested in the X direction. Tensile modulus specimens were machined per ASTM D3039-76 and flexural modulus specimens per ASTM D790-71. Strain was measured by electrical resistance strain gages. Minimum replication is four samples.

TABLE 3.

Plaque Thickness		E_t		E_f	
inch	(mm)	10^6 psi	(GPa)	10^6 psi	(GPa)
0.125	(3.2)	1.95	(13.4)	2.34	(16.1)
0.241	(6.1)	1.61	(11.1)	2.09	(14.4)
0.466	(11.8)	1.14	(7.9)	1.97	(13.6)

It should be noted that the tensile modulus E_t as measured by experiment may be slightly high due to bending-tension coupling effects set up by the asymmetry of the fiber boundary layers [3]. This was assumed to be a second order effect. Similarly, the measured strain results were averaged for the top and bottom surfaces to eliminate the asymmetry effects in the flexure test.

Thermal Expansion Coefficients. Samples of the boundary layer and center layer were machined from the plaques by using a surface grinder equipped with a diamond wafering saw. Thermal expansion coefficients were measured between room temperature and 175°F (80°C) using electrical resistance strain gages. Again, the aligned fiber boundary layer contained fibers primarily in the X direction, and the center layer contained fibers primarily in the X-Y plane. The results are shown in Table 4.

TABLE 4.

Layer	Thermal Expansion Coefficients			
	α_X		α_Y	
	$\mu\varepsilon$/°F	($\mu\varepsilon$/°C)	$\mu\varepsilon$/°F	($\mu\varepsilon$/°C)
Boundary	12	(22)	34	(61)
Center	27	(49)	30	(54)

DISCUSSION AND CONCLUSIONS

The existance of "boundary layers" of aligned fibers near the mold walls can be clearly seen from the photomicrographs. The boundary layers can be clearly distinguished from the center section, and layer thicknesses may be measured. In general, the boundary layer thicknesses seem to reach a fixed thickness for any plaque greater than about 0.25 inch (6.4 mm) thick. The layers tended to be asymmetric, with the "top" boundary layer thickness different from the "bottom" boundary layer thickness. One possible explanation for the asymmetry is a temperature difference in the mold. Molten material in contact with the cooler surface would be expected to have a higher viscosity, promoting an increase in thickness in the aligned fiber boundary layer.

The aligned fiber boundary layers near the mold walls had a dramatic effect on mechanical properties and warpage. Tensile modulus steadily declined with increasing part thickness, since the higher modulus boundary layers occupied a smaller proportion of the net section. The boundary layers seemed to reach a stable thickness above about 0.25 inch (6.4 mm) thick sections. Therefore, a continued decrease in modulus with increasing part thickness would be anticipated in the mold fill direction.

Given effective tensile moduli for the plaque, and given the layer thicknesses within the plaque, we can estimate the moduli of boundary and center layers. To do this, we use a "rule of mixtures" approximation:

$$E_t = A_B E_B + A_C E_C$$

where E_t is the effective (measured) tensile modulus;

A_B, A_C are the percent areas of the boundary layer and center layer, respectively; and

E_B, E_C are the moduli of the boundary and center layers, respectively.

Using experimental modulus measurements from the 0.24 and 0.46 inch (6.1 and 11.8 mm) plaques yields the following estimates for tensile modulus:

$$E_B = 2.30 \times 10^6 \text{ psi} \quad (15.9 \text{ GPa})$$

$$E_C = 0.69 \times 10^6 \text{ psi} \quad (4.8 \text{ GPa})$$

Applying these estimates to the 0.125 inch (3.2 mm) plaque, we predict a tensile modulus of 2.08×10^6 psi (14.3 GPa), which compares quite favorably to the experimental value of 1.95×10^6 psi (13.4 GPa).

The thickness effect of the flexural modulus was similar to that of the tensile modulus. However, since flexural modulus is a function of the product of the area of aligned fibers and the cube of the distance from the neutral surface, the flexural modulus decreases less

rapidly than the tensile modulus as the plaque thickness is increased. In fact, the apparent modulus reflected by the flexural test can be misleading and unconservative when used as design data for other than flexural applications. Hence, it is imperative that the designer consider the in situ state of orientation in the molded part and the accompanying variations in material properties in his design.

The warpage experienced in thicker cross sections can be traced to the geometric asymmetry of the boundary layers and the mismatch in thermal expansion coefficients. The thermal expansion of the boundary layer is significantly lower than that of the center in the aligned fiber (X) direction. Thus during cool-down after molding, the plaques will contract differentially causing residual thermal stresses. If the boundary layers were symmetric (top and bottom layers of the same thickness), there would be no warpage in spite of the residual thermal stresses induced. Warpage was most noticeable in the plaques thicker than 0.25 inch (6.4 mm).

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REFERENCES

1. D. G. Taggart, R. B. Pipes and J. C. Mosko, "Test Method Evaluation for Fiber-Reinforced Molding Materials," Polymer Engineering and Science, (in press).

2. C. D. T. Wu and R. L. McCullough, "Constitutive Relationships for Heterogeneous Materials," Developments in Composite Materials, Vol. 1, Applied Science Pub., London, 1977, pp. 119-187.

3. N. J. Pagano and J. C. Halpin, "Influence of End Constraint in the Testing of Anisotropic Bodies," Journal of Composite Materials, Vol. 2, No. 1, January 1968, pp. 18-31.